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Latent heat thermal storage with variable porosity metal matrix: A numerical study

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ABSTRACT

In this paper, a novel design of multitube shell and tube latent heat thermal energy storage system (LHTES) with variable porosity metal matrix in PCM is presented. The shell side of the LHTES contains a phase change material, whereas heat transfer fluid (HTF) flows through seven tubes with internal fins. Metal matrix, as a thermal conductivity enhancer (TCE), is used to augment heat transfer in PCM, however the temperature distribution in PCM is found to be non-uniform along the length of the storage system for constant porosity metal matrix in PCM, which affects the thermal performance of the LHTES. A numerical model is developed to investigate the fluid flow and heat transfer characteristics using the momentum equation and the two-temperature non-equilibrium energy equation coupled with the enthalpy method to account for phase change in PCM. The numerical model is first validated with the experimental results and further extended to identify the effects of geometrical parameters on the temperature distribution in PCM. A relationship between porosity and ratio of length to annular diameter of the storage system is developed for porosity varying from 0.95 to 0.85. It is found that the size of LHTES with variable metal matrix porosity can be reduced for the same effectiveness.

1. Introduction

Solar radiation is one of the abundant renewable sources of energy that can be utilized to generate electricity for small scale (~0.1 MW) solar thermal applications. The major issue with the solar based systems is the inability to generate electricity continuously due to the intermittent nature of sun radiation. A thermal energy storage can fill the gap between demand and supply of the energy. Energy can be stored in the form of sensible heat and latent heat. Latent heat thermal energy storage system uses phase change materials (PCM) which has advantages over sensible heat storage system, as it can exchange heat within a small temperature difference and also it has high latent heat of melting that makes the storage more compact. However, a major drawback with PCM is its low thermal conductivity which often reduces the effectiveness of the storage system. Enhancement of heat transfer in PCM can be achieved by either increasing heat transfer on internal heat transfer surface or exchanging heat storage medium [1]. Some of the commonly used techniques to argument the heat transfer in PCM are embedding PCM in metal matrix [2–4], random packing of carbon fibre in PCM [5,6], using composite such as graphite in PCM [7], metallic dispersion in PCM [8,9], encapsulation [10–13], addition of fins [14–17], ring and bubble agitation in PCM [18].

The shell and tube type heat exchanger is widely used configuration to study latent heat thermal storage system (LHTES). In this paper, shell and tube type latent heat thermal storage system based on solid-liquid phase change is analyzed. The phase change material is packed in the annulus of the heat exchanger and heat transfer fluid (HTF) flows though the tubes inside the shell. Metal matrix is inserted in PCM as thermal conductivity enhancer (TCE) to improve heat transfer in PCM. Several studies have been carried out to understand the effect of metal matrix as TCE on thermal storage system. In a numerical study carried out by Mesalhy [4] on LHTES, heat transfer in PCM is found to increase by inserting high porosity metal matrix in PCM. The melting of PCM with metal matrix shows significant difference as compared to PCM without any thermal conductivity enhancer. PCM with metallic porous matrix is numerical analyzed by Bejan [19] considering thermal equilibrium between metal matrix and PCM. The results showed that heat transfer and melting rates are significantly affected by the liquid Stefan number. Thermal equilibrium model between metal matrix

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Nomenclature

a_{sl}	Interfacial surface area [m^{-1}]
c_p	Specific heat [J/kg.K]
C	Inertial coefficient [−]
d_o	Outer diameter of HTF flowing tube [m]
d_p	Pore diameter [m]
d_{fi}	Fibre diameter [m]
D	Annular diameter (D_o-d_o), [m]
D_o	Diameter of numerical domain, [m]
E	Enthalpy [J/kg]
ΔE	Nodal latent heat [J/kg]
f_l	Liquid fraction
g	Acceleration due to gravity [m/s^2]
h_{sl}	Interfacial heat transfer coefficient in porous medium [$W/m^2.K$]
H	Height [m]
H_f	Height of fin [m]
k	Thermal conductivity [W/m.K]
k_f	Thermal conductivity of fin material [W/m.K]
K	Permeability
L	Length of LHTES [m]
L^*	Non-dimensional length $\left(L^* = \frac{z}{L}\right)$
L_{latent}	Latent heat of fusion [J/kg.K]
$\dot{m}$	Mass flow rate of HTF [kg/s]
Nu	Nusselt number
P	Pressure [N/m^2]
Q	Heat transfer [J]
r, θ, z	Coordinates
Re	Reynolds number
t	Time [s]
t_f	Thickness of fin [m]
T	Temperature [°C]
T_d	Discharging temperature [°C]
u_r, u_θ, u_z	Velocity component in *r, θ and z* directions [m/s]
V	Volume [m^3]

Greek symbols

α	Thermal diffusivity [m^2/s]
β	Thermal expansion coefficient [K^{-1}]
ε	Porosity
μ	Dynamic viscosity [kg/m.s]
ρ	Density [kg/m^3]
Ψ	Tortuosity
η	Efficiency
θ	Non-dimensional temperature $\left(\frac{T_{in}-T}{T_{in}-T_{initial}}\right)$

Subscripts

c	Charging
d	Discharging
eff	Effective value
htf	HTF
in	Inlet
l	Liquid
$LHTES$	Latent heat thermal energy storage
m	Melting point
p	PCM
out	Outlet
s	Solid
$total$	Total
$Unit$	Unit cell

and PCM was numerically studied by Beckermann and Viskanta [20]. The model is validated with experiments, however the thermal equilibrium model is justified as the thermal conductivity difference metal matrix and PCM is very low. Whitaker [21] suggested that a significant deviation in thermal equilibrium model can be found if the differences in the physical properties of solid and liquid are large. At high Rayleigh and Darcy numbers, the two-energy equation model shows the considerable deviation from the local thermal equilibrium model [22]. Recently, Kumar and Saha [23] evaluated the first and second law efficiencies of LHTES with constant porosity metal matrix during charging and discharging processes. The effects of storage material, porosity and pore-diameter on the net useful energy that can be stored and released during a cycle, are studied. It was found that the first law efficiency of sensible heat storage system is less compared to LHTES. With the decrease in porosity, the first law and second law efficiencies of LHTES increase for both the charging and discharging periods. There is no significant variation in energy and exergy efficiencies with the change in pore-diameter of the metal matrix. Zhang and He [24] investigated the melting of PCM infiltrated in the metal foam of porosity varying from 85.9% to 95.5% considering local thermal equilibrium between the porous metal and PCM. Authors concluded that the metal matrix with varying porosity increases the heat transfer rate in PCM.

From the available literature, it is found that extensive studies on heat transfer characteristic and performance of latent heat storage system with metal matrix are performed. Most of the studies reported that the porosity of metal matrix affects the performance of storage system significantly. However, all the studies on latent heat storage system with metal matrix in PCM considers homogenous porosity of the matrix. Although metal matrix with constant porosity in PCM enhances the thermal performance of the LHTES, the temperature distribution in PCM can be non-uniform along the length of the storage system, which causes non-uniform heat transfer between PCM and TCE, results in the reduction of thermal performance of LHTES. The uniformity in heat transfer within PCM can be achieved by incorporating metal matrix with variable porosity, which is studied and analyzed in this work. A numerical model is developed to investigate the fluid flow and heat transfer characteristics using the momentum equation and the two-temperature non-equilibrium energy equation coupled with the enthalpy method to account for solid-liquid phase change in PCM. Cyclic charging and discharging period of 1800 s each is considered for this analysis. Parametric studies are performed to identify the important geometrical parameters of the storage system affecting the melt fraction and temperature distribution in PCM during charging and discharging processes. Further, an expression for variable porosity based on the geometric parameters is developed to study the thermal performance of LHTES.

2. Physical domain

A multitube shell and tube heat latent heat storage system is considered, which consists of equi-spaced tubes enclosed by a shell, as shown in Fig. 1. In multitube shell and tube arrangement, the formation of multiple convective cell and augmented convection in the multitube subsequently lead to the enhancement of heat transfer between HTF and PCM as compared to the single tube unit [25]. In the present study, the diameter of the shell is considered as 100 mm, with the length of the storage unit as 800 mm. The outer